Effects of Aging and Environmental Conditions on Ammunition/Explosives Storage Magazines – Paper 1

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Abstract

The Defense Ammunition Center (DAC)/U.S. Army Technical Center for Explosives Safety (USATCES) recognized the need to establish the 'structural health' status of aging ammunition/explosives storage magazines. A recent accidental explosive event in an earth covered magazine demonstrated that legacy assumptions for structural failure may be unknown and potentially adversely affect safety. Aging and the effects of environmental factors may have an effect in the structural performance of the storage magazines when subjected to explosions. DAC requested the assistance of the University of Oklahoma, USACE-ERDC (Vicksburg), and USACE Engineering and Support Center to determine the 'structural health' of aging magazines, evaluate remediation methods, and perform structural analyses to duplicate structural conditions found in situ magazines. The key goals of the effort (July 2008 thru May 2010) are to gain an accurate estimate of scope of the problem of deficient magazines, to collect and archive data on the structural health of existing magazines, to identify practical remediation methods for risk-graded magazine renovation efforts, and to create a long-term health monitoring program for

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14. ABSTRACT

The Defense Ammunition Center (DAC)/U.S. Army Technical Center for Explosives Safety (USATCES) recognized the need to establish the structural health status of aging ammunition/explosives storage magazines. A recent accidental explosive event in an earth covered magazine demonstrated that legacy assumptions for structural failure may be unknown and potentially adversely affect safety. Aging and the effects of environmental factors may have an effect in the structural performance of the storage magazines when subjected to explosions. DAC requested the assistance of the University of Oklahoma, USACE-ERDC (Vicksburg), and USACE Engineering and Support Center to determine the structural health of aging magazines, evaluate remediation methods, and perform structural analyses to duplicate structural conditions found in situ magazines. The key goals of the effort (July 2008 thru May 2010) are to gain an accurate estimate of scope of the problem of deficient magazines, to collect and archive data on the structural health of existing magazines, to identify practical remediation methods for riskgraded magazine renovation efforts, and to create a long-term health monitoring program for continuation of this important effort. Environmental conditions that could adversely affect the structural health of the magazine were determined and several installations (CONUS and OCONUS) were visited to perform visual inspections and gather material samples that were laboratory tested. Modeling this effort after the proven DoD Bridge Inspection program, a magazine inspection checklist was developed. A web-accessible data archive was developed to support storage and retrieval of magazine inspection data. This presentation will provide general information about the effort, discuss the decision process to determine what DoD installations were visited, development of the site inspection checklists, type of material samples that were taken and the web-based data base that was developed.

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This presentation will provide general information about the effort, discuss the decision process to determine what DoD installations were visited, development of the site inspection checklists, type of material samples that were taken and the web-based data base that was developed.

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Mr. Jeff Coulston has worked with the U.S. Army Engineering and Support Center, Huntsville since 1998. Since 2004, Mr. Coulston is currently Chief of the Structures Branch. Mr. Coulston is a registered professional engineer in the state of Alabama and earned his Bachelor of Science degree in Civil Engineering from Tennessee Technological University. Mr. Coulston oversees his branch's explosives effects, protective construction mitigation and siting support to various Air Force, Air National Guard, Army and DoD customers.

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Introduction

Explosives safety standards are set forth by the Department of Defense (DoD) in DoD 6055.09-STD – DoD Ammunition and Explosives Safety Standards [1] and the Department of the Army Pamphlet 385-64 – Ammunition and Explosives Safety Standards [2]. The DoD explosives safety management policy is to expose the minimum number of people for the minimum time to the minimum amount of explosives consistent with safe and efficient operations. The goal is to provide the maximum possible protection to people and property from the potential damaging effects of DoD military munitions.

DoD missions require the storage of ammunition and explosives. Earth-covered magazines, or ECMs, are a common form of military structure used to store volatile chemical products, including explosives and sensitive fuels. The Department of Defense Explosives Safety Board (DDESB) published Technical Paper (TP) 15 'Approved Protective Construction' [3] provides a record of historically significant information about the origin and evolution of protective construction designs, including ECMs, that have been built over the past 80 years and the explosives safety criteria associated with them. When an ECM is the Exposed Site (ES), its primary purpose is to protect its' contents and to prevent propagation of explosion. When the ECM is the Potential Explosion Site (PES), the potential resulting explosives effects of concern are blast, fragments, and thermal hazards.

While there are many types of ECMs on DoD installations, the various structural forms usually arise from variations on a common theme, that of a steel or reinforced concrete structure with either single- or double-curvature in its roof (i.e., vaults or domes), headwall (including door), and rear wall with earth cover over all components except the headwall. Some descriptive terms commonly used to identify these 'types' of ECMs are 'bunkers' and 'igloos'. This effort concentrates on the reinforced concrete arch type Earth-covered magazines.

Earth-covered magazines have been built for decades in the United States, and many of these structures are showing signs of age, including degradation of the structural concrete due to various environmental effects, as well as larger-scale structural vulnerabilities arising from cracks and other forms of concrete structural degradation. For various reasons, some magazines were built with less-than-optimal steel reinforcement, and hence their structural health is suspect. Others have experienced substantial degradation and corrosion of this reinforcement, resulting in similar concerns about structural health. And periodically, explosives accidents occur within these magazines, and the resulting loss of life and property yields concerns about how 'aging' may affect magazine performance related to current explosives safety standard criteria.

This research project began with a compelling idea arising from the technical staff at the U.S. Army Technical Center for Explosives Safety's Defense Ammunitions Center (DAC). In the aftermath of an explosion at the Milan, Tennessee Army munitions facility in 2004, DAC personnel began investigations into the feasibility of establishing a clearinghouse for information on ECMs, towards the goal of performing science-based investigations into the causes and effects of explosives accidents.

At Milan, two workers were killed and another seriously injured by an explosion from volatile fuels stored in an ECM. The structural 'break-up' of the Milan magazine did not conform to generally-accepted design principles, as large parts of the barrel vault structure were found well outside the range of distance expected. This explosion ended approximately four decades of fatality-free work at Milan, and caused explosives safety experts to reconsider idealizations of how an ECM behaves during an internal explosion. The accident at Milan specifically indicated that these structural idealizations may be un-conservative, so that the effects of such accidents might engender greater risks to the surrounding magazines, and to the public at large, than previously expected.

In particular, questions have arisen as to whether structural vulnerabilities such as cracking of the ECM's vault ceiling might have resulted in the concentration of blast momentum in a few large pieces of the damaged structure, instead of said momentum being evenly distributed over relatively small pieces of the vault, which would then fall to earth somewhat nearby or more closely within the distance expected as representative in current DoD and DA standards. In much the same way as an aneurysm forms in the weak spot of a blood vessel under internal pressure, a similar concentration of mechanical response might be an unwelcome side-effect of aging of the concrete components of magazine structures.

This project was designed to initiate a scientific study of the effects of aging on earth-covered magazines, including physical and chemical inspections of a wide variety of magazines from five different geographically-diverse. By leveraging ERDC-WES efforts related to the Bridge Inspection program, site inspections were performed on one hundred twelve (112) ECMs and concrete core samples were taken from three of the installations visited. These inspection results were catalogued within an information archive so that these records can be preserved, compared, and evaluated over time. In addition to these physical inspections, various structural analyses were also carried out to learn how virtual inspection techniques could be used to supplement real-world inspection results from field examination of these structures.

This paper provides general information about the effort, discusses the decision process to determine what DoD installations were visited, development of the site inspection checklists, type of material samples that were taken and the web-based data base that was developed. In addition to this work performed under the aegis of this project, this paper also includes suggestions for future work, both in terms of natural extensions of the project's results, but also new work intended to better characterize the structural health of the entire inventory of ECM's, so that cost-effective measures to remediate structural health problems can be developed and implemented in the near term. A related paper 'Effects of Aging and Environmental Conditions on Ammunition/Explosives Storage Magazines – Paper 2' discusses environmental conditions that adversely affect the structural health and life of a magazine. In Paper 2, the type of material testing and results will be presented along with the results of finite element structural analyses performed to assess and predict the structural condition found in the site inspections.

Team Make-Up

The scope of this effort required technical team members with knowledge of structural engineering, explosives effects, explosives safety standards, construction materials, field inspections, remediation techniques, and information technology.

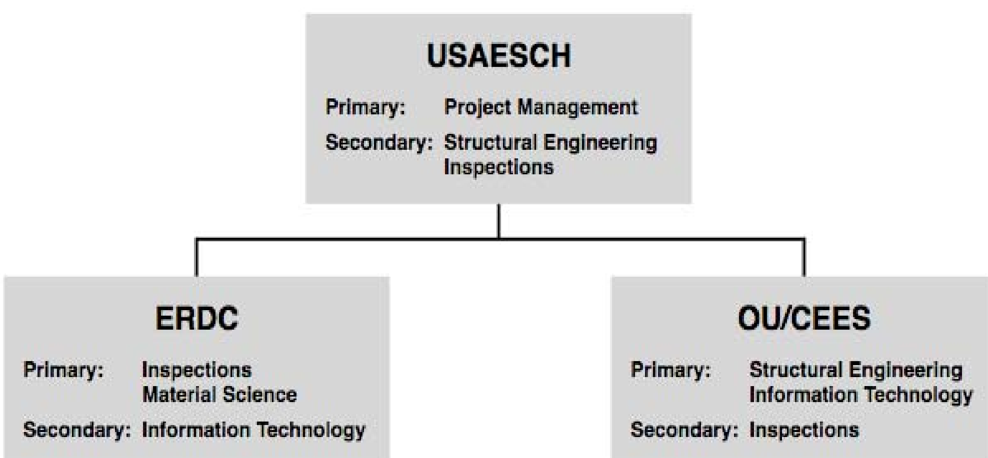


Figure 1 Organization Chart

- The U.S. Army Engineering and Support Center, Huntsville (USAESCH) has a long history of providing explosives effects and protective construction consultation to numerous DoD and private industry organizations. USAESCH is the designated design agent for several standard Earth Covered Magazines approved by the DDESB.
- The U.S. Army Engineer Research and Development Center (ERDC) is well known for their expertise in many areas related to this effort, more specifically, performing site inspections and material testing to determine the deterioration effects of the environment on reinforced concrete structures and proposed remediation techniques.
- The University Of Oklahoma College Of Engineering (OU/CEES) has a diverse set of faculty and student talents that were provided for this research project, including faculty members with specific expertise in structural analysis, information technology, structural health monitoring, concrete response, soil-structure interaction, and structural experimentation.

Project Scope

The scope of the project is defined by four component tasks, each of which is intended to realize one of the project goals, and the sum of which provides a scalable prototypical effort that realizes the motivations of this research project. These four components tasks are defined below.

(1) the development of a data-collection plan for a representative sample of ECMs as found in a geographically diverse set of military sites. This data-collection enterprise involves deliberation among the project principals towards the goal of selecting a sample of inspection activities that forms a good compromise between a low-cost prototype inspection regimen and a sufficiently comprehensive set of inspections for populating a working data archive of site inspection results.

(2) the collection of inspection data from the candidate sites, including development of inspection forms, site visits for carrying out inspection activities, visual inspections, taking of samples for laboratory analysis, and populating the various database iterations so that these catalogs of inspection data can be archived and retrieved for later use. This task includes the design, implementation, and incremental improvement of the data archive, with a total of three incremental versions of the database, using (a) spreadsheet technology, (b) a simple relational database, and (c) a fully-scalable database version utilizing a web-based interface.

(3) identification of appropriate structural remediation techniques, including a review of results from similar problems of structural health, e.g., bridges and other large-scale critical infrastructure. A particular form of remediation that has proven useful in other engineering venues is the use of computer simulation methods for examining structural response, so that future remediation efforts might be based on inexpensive and safe computational analyses instead of on more expensive and difficult alternatives such as inspections of ECMs that are involved in day-to-day use.

(4) a plan for carrying out a longer-term monitoring program of structural inspections of candidate ECM's, including future inspections of the sites already visited, and an expansion of the candidate sites to include additional explosives storage facilities. This open-ended monitoring program necessitates of the use of production-grade database technology, and so this task provided guidance on the design of the data archive developed in the third task. Best-practices monitoring examples can be drawn from current and past governmental efforts

in similar engineering settings, e.g., Federal Highway Administration (FHWA)'s long-term pavement monitoring program, or National Nuclear Security Association (NNSA)'s stockpile surveillance initiative.

Earth-Covered Magazines Overview

Per DoD 6055.09-STD [1], ECMs either have a structural designation of 7-bar, 3-bar, or Undefined. These designations indicate the level of blast pressure and impulse the ECM can mitigate if subject to an accidental explosion (ie. ECM is an Exposed Site). The structural designations are also considered when determining the required Quantity Distance (QD) between various PES – ES combinations.

The effect of earth cover has been documented during testing to indicate that the blast overpressure and debris throw is somewhat channeled to the portion of the ECM that does not have earth cover. For example: the debris throw distance and overpressure values are farther/larger out the front of an ECM with earth cover on the sides, rear, and roof. The current QD tables in DoD standards reflect this channelization of blast effects. The debris throw distances related to the various permissible exposures (IBD, PRTD, ILD, and IMD) are based on the conditions of the structural components during testing and/or assumptions at the time of design. The test conditions and design assumptions would not have considered or represented the effects of 'aging/deterioration" that some of existing DoD ECMs may be experiencing.

ECMs are constructed in several different configurations, but most of these important buildings contain some or all of the following structural components:

- side walls and roof (arched or flat): an arched roof is generally found in single curvature, and which is usually constructed of corrugated steel or reinforced concrete. This effort did not include steel arched type ECMs. The side walls and vaulted roof are not designed to contain internal explosions, but to provide open floor space within the magazine, and they are detailed so that its structural response to an internal blast can be assumed as a uniform fragmentation into concrete rubble which moves upward and outward. A flat room must mitigate the blast loading criteria given in DoD 6055.09-STD [1].
- reinforced concrete headwall (front) and end wall (rear): For most ECMs the rear wall is covered with earth similar to the side walls and roof. A 7-bar and 3-bar headwall usually consist of a robust door, robust pilasters beside the door, and a robust header above the door that has been designed or tested to meet the respective blast criteria stated in DoD 6055.09-STD [1]. An Undefined headwall will usually contain the same components, but are not robust enough to meet 7-bar or 3-bar criteria. These headwalls may be integrated into adjacent wing-walls that extend laterally beyond the headwall and aid in containing the earth overburden on the structure.
- an earth covering over the top and sides of the magazine, that provides additional mass to trap momentum of blast loads arising either internally by enclosed explosions or externally via blast effects from adjacent magazines. Earth cover must be a minimum thickness (2') and meet requirements set forth in DoD 6055.09-STD [1].
- a reinforced concrete floor upon which volatile components such as explosives or sensitive fuels are placed. This floor may be sloped to permit drainage, and it rests on foundation soil.

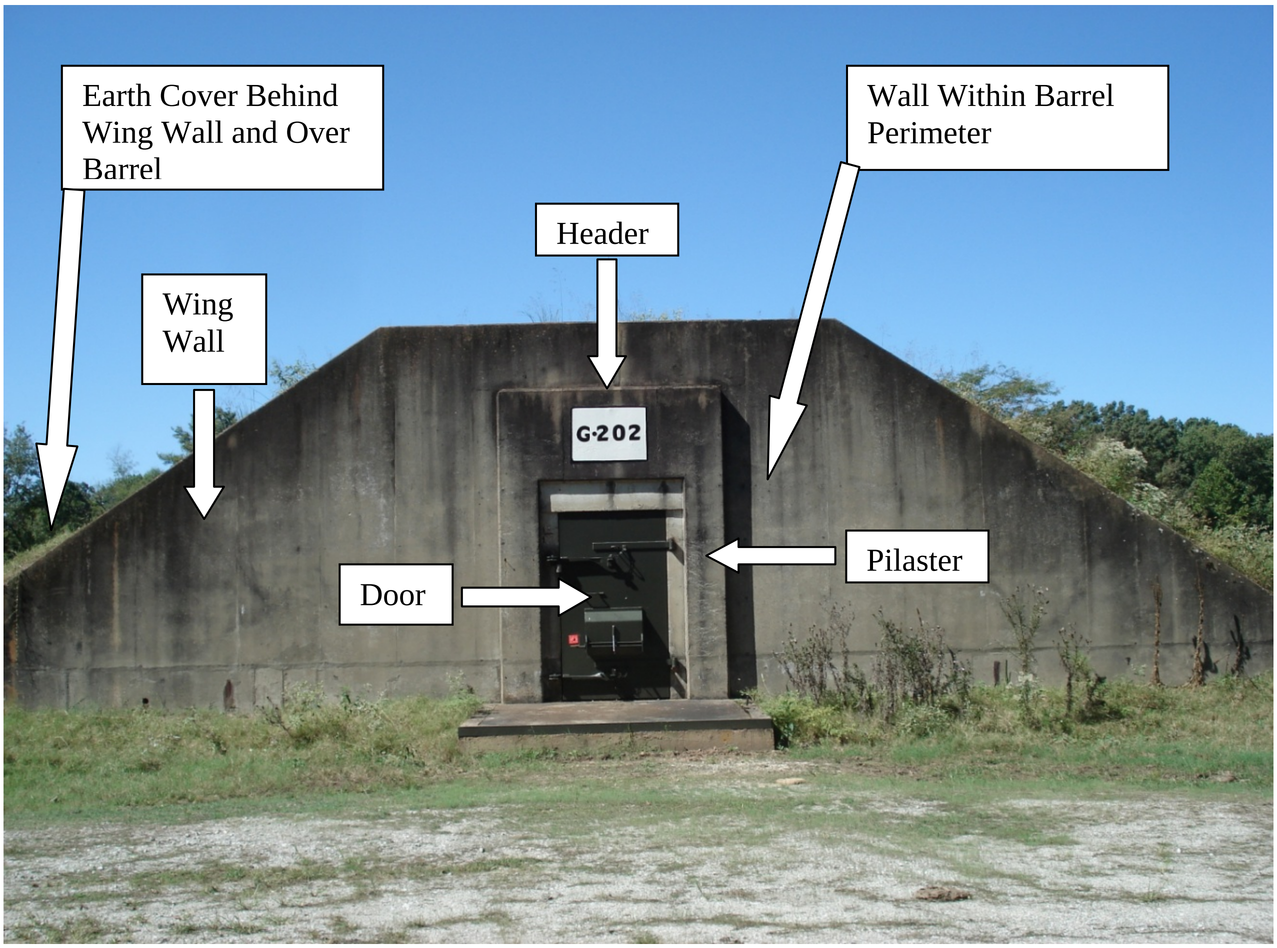


Figure 2 ECM Exterior Components

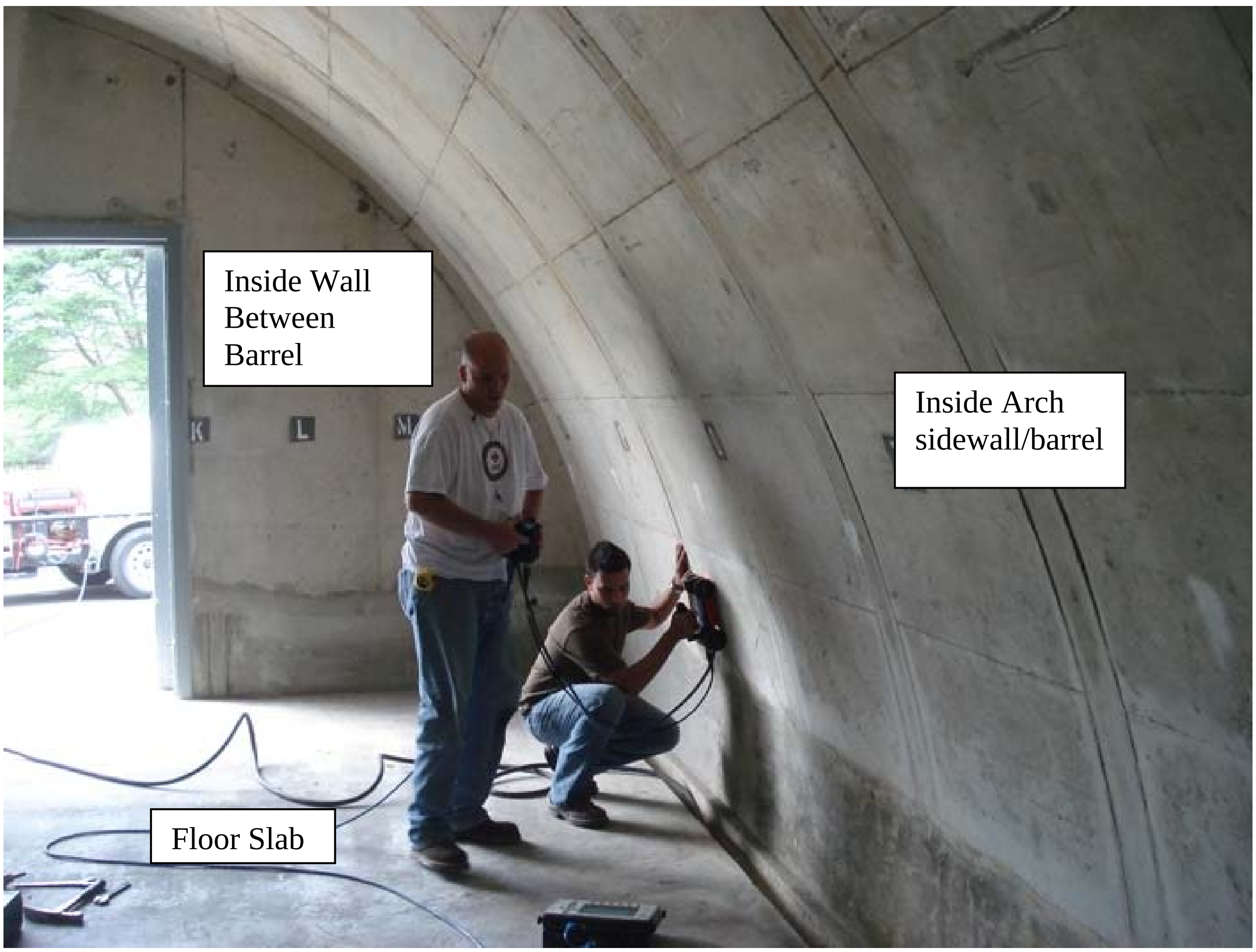


Figure 3 ECM Interior Components

Determination of Installations to Perform Site Inspections

This effort is being focused on reinforced concrete structures and proposed site were selected based on environmental and geologic factors know to be related to the degradation of reinforced concrete structures.

In understanding the degradation of any structure, it is an important matter to know how to properly understand the nature and severity of the environment of service. This helps define a reasonable estimate of its intended or remaining service life. The remaining service life can be estimated based on the visual inspection and later by destructive testing and non-destructive testing. This also helps to get an assessment of how much degradation is tolerable structurally and operationally. Relative to some relatively fragile sedimentary rocks exist that has survived some hundreds of millions of years, there are concretes that, in relatively mild environments, that could last forever or at least as close to "forever" as we can measure.

Overview of Concrete Deterioration

Chemical Reactions

- **Acid Attack:** Portland cement concrete is highly alkaline material and is not very resistant to attack by acids. The deterioration of concrete by acids is primarily the result of a reaction between the acid and the products of hydration of cement and carbonate aggregates. Calcium silicate hydrate may be attacked by acids with a pH of 5 or less which may exist in the environment of the concrete structure. In most cases, the chemical reactions result in the deterioration of the microstructure and the dissolution of water-soluble calcium compounds that are then leached away. Based on the location chosen to inspect there will be some background knowledge about the surrounding environmental conditions. With the background knowledge it is easier to detect deterioration during visual inspections. The degree of aggressiveness of the acid attack will determine how rapidly structural integrity will be lost. Acid attack will eventually cause loss of structural strength and the ability to protect the reinforcing bars from corrosion. This can be seen as loss of section, spalling, or efflorescence.

- **Aggressive-water attack:** Some waters have been reported to have extremely low concentrations of dissolved minerals. These soft or aggressive waters leach calcium from the cement paste or aggregates. It should be noted that this phenomenon does not have a high frequency of reporting in the United States. Aggressive-water attack, although rarely seen, serves to deteriorate the chemical binder that holds concrete together. This type of deterioration could be seen as efflorescence, spalling, or loss of section.

- **Alkali-Carbonate rock reaction (ACR):** Certain carbonate rock aggregates have been proven to be reactive in concretes. The results of these reactions have been characterized as destructive. The destructive category is apparently limited to reactions with impure dolomitic aggregates and are a result of either dedolomitization or rim-silicifation reations. Visual investigation of those reactions that are serious enough to disrupt the concrete in a structure will generally show map or pattern cracking, a general appearance that the concrete is swelling. Swelling of the internal concrete causes extreme pressures that eventually overcome the tensile strength of the structure. These pressures will cause spalling, map cracking, discoloration, or bulging which in turn eventually affects the structural integrity. ACR can reduce the intended service life based on the deterioration rate.

- **Alkali-Silica reaction (ASR):** Some aggregates containing silica that are soluble in highly alkaline solutions may react to form a solid nonexpansive calcium-alkali-silica complex. On the other hand, they may form an alkali-silica complex which can consume considerable amounts of water and subsequently expand, damaging the concrete. ASR damages concrete by the silica forming a gel in the open pore spaces and expanding. Over time the pore spaces fill with this gel and expand creating extreme tensile pressures. These pressures cause micro cracking and eventually structural cracks. These cracks generally show up as map cracking. There is also a white substance that has a bluish tint to it. Once these expansive pressures start to damage the structure it will compromise the structural integrity. Visual examinations of those concrete structures affected will show map or pattern cracking and a general appearance that indicates the concrete is swelling.

- **Sulfate attack:** Naturally-occurring sulfates of sodium, potassium, calcium, or magnesium are sometimes found in soil or in solution in ground water adjacent to concrete structures. The sulfate ions go in to solution and can attack the concrete. There are two sequential chemical reactions that take place in sulfate attack on concrete. The first one is that the sulfate reacts with the free calcium hydroxide which is liberated during the hydration state of the cement to form calcium sulfate (gypsum). Next the gypsum reacts with the hydrated calcium aluminate to form calcium sulfoaluminate (ettringite). Both of these reactions cause a large increase in volume. The second reaction is mainly responsible for the volume change of the concrete. When volume changes occur in concrete it causes extreme pressures that overcome the tensile strength of the concrete. These extreme pressures seen either as shrinkage or expansion will cause cracking. Visual inspection of these structures will show map or pattern cracking and a general deterioration of the concrete.

- **Carbonation of Concrete:** The high alkalinity of the concrete can be reduced over a long period of time by carbonation. Carbonation occurs in concrete because the calcium bearing phases present are attacked by the carbon dioxide of the air and converted to calcium carbonate. The pH of fresh cement paste is about 12.5 – 13 fully carbonated paste has a pH of 8.5 or below. The range of pH in the concrete will be determined by the use of phenolphthalein. By saturating a freshly broken surface of concrete with phenolphthalein the surface will change colors to purple if the pH has dropped below 9.5.

- **Corrosion of the Reinforcing Steel:** Steel reinforcement is normally placed within a 2 inches of a concrete surface. Under most conditions, Portland cement provides good protection to the reinforcing steel. The protection of the steel is generally accredited to the high alkalinity of the concrete. The steel is also protected by the relatively high electrical resistance of the concrete. Still, corrosion of the reinforcing steel is one of the most frequent causes of damage to concrete structures. The high alkalinity of the concrete can be reduced over a long period of time by carbonation. The electrical resistivity can also be decreased by the presence of chemicals in the concrete. The chemical most commonly applied to concrete is chloride salts in the form of deicers.

  In most cases with ECMs this form of deterioration may not present a problem. However, a large majority of these structures have loading docks or concrete padded areas outside the door. In areas where large amounts of snow are accumulated it is possible for de-icer salts to be used to keep the loading area free of snow. As the chloride ions penetrate the concrete, the capability of the concrete to carry electrical current increases. If there are differences within the concrete such as moisture content, chloride content, oxygen content, or if dissimilar metals are in contact, then there is potential for a corrosion cell to occur. The anodes will experience corrosion (generally the reinforcing steel) where the cathodes will remain undamaged. As reinforcing steel corrodes it expands and causes tensile pressures to force the concrete/reinforcement steel bond to break. Corrosion of the steel will cause spalling, section loss of the steel, and eventually the loss of all tensile strength to the concrete.

Improper location of the reinforcing steel is another issue that will affect the performance of a concrete structure. If the reinforcing steel is not properly located it may not function structurally as intended. One of the more common issues with misplacement of the reinforcing steel is insufficient concrete cover. Since the concrete cover over the steel is reduced, it is much easier for corrosion to begin.

All of the above deterioration conditions can cause the concrete to separate into large structural sections. During a blast event the separated areas provide areas of least resistance. This may alter the size (i.e. larger than usual) of the secondary debris especially for low loading density events.

Mechanical Damage

- **Freeze/ Thaw damage:** As the temperature of a critically saturated concrete is lowered during cold weather, the freezable water held in the open voids (commonly called capillary pores) of the cement paste and aggregates expands upon freezing. If subsequent thawing is followed by the refreezing, the concrete is further expanded, so that repeat cycles of freezing and thawing have cumulative effect. This same behavior is observed for the freezing of water in the voids of many rocks used as aggregates, and in large voids or cavities in concrete. The total amount of pore space and the size and distribution of these pores, and their continuity is important in determining durability. Voids filled with water that begins to freeze it will force the remaining water to find relief space in other open voids; therein, causing internal hydraulic pressures. These pressures will depend on the porosity of the concrete. If there is not sufficient pore space then the internal hydraulic pressures will be great enough to break or crack the concrete.

  By their nature, concrete structures exposed to frequent saturation are particularly vulnerable to freezing and thawing simply because there is ample opportunity for portions to become critically saturated. The use of deicing chemicals on concrete surfaces may also accelerate damage caused by freezing and thawing and may lead to pitting or scaling. Since this damage method can reduce the effective concrete cover in the concrete, it can lead to accelerated corrosion of reinforcing steel in the structure. Additionally, since cracks or voids are created in the concrete, they can act as conduits for contaminants that can accelerate chemical attack on the concrete and reinforcing steel.

- **Structural Movement:** In structure settlement, it is common for various elements of a structure to moving with respect to one creating differential movements. Differential movement can be caused by various types of soils or the erosion of soils. Areas with expansive clays will experience differential movement based on the expansion of the underlying soil. Since concrete structures are typically rigid, they can only endure very little differential movements. As the differential movement increases, concrete members can to be subjected to overstressed conditions. Eventually the members will crack or spall. Again, these failures may reduce cover and/or act as conduits for reactive chemicals.

- **Shrinkage:** Shrinkage is caused by the loss of moisture from concrete. It may be divided into two categories (1) that which occurs before setting (plastic shrinkage), and (2) that which occurs after setting (drying shrinkage). Shrinkage also occurs when carbonation of concrete takes place and when the concrete is exposed to thermal events.

- **Plastic Shrinkage:** During the period between placing and setting, most concrete will exhibit bleeding to some degree. Bleeding is the appearance of moisture on the surface of the concrete; it is caused by the settling of the solid components of the mixture. Usually, the bleed water evaporates slowly from the surface of the concrete. If environmental conditions are such that evaporation is occurring faster than bleeding, high tensile stresses can develop. These stresses can lead to the development of cracks at the surface. These cracks can lead to allowing more water into the system which could then lead to steel corrosion and on to spalling of the concrete.

- **Drying Shrinkage:** Drying shrinkage is the long-term change in volume of concrete caused by the loss of moisture. If this shrinkage could take place without any restraint, there would be no damage. However, the concrete structure is always subject to some degree of restraint by either the foundation, by another part of the structure, or by the differences of shrinkage of the surface to the interior members. The combination of shrinkage and restraints can cause tensile stresses that produce cracks.

- **Seismic Vulnerability:** The effects of seismicity on earth covered magazines include a wide range of structural effects which depend greatly upon the local intensity of the earthquake and on how well the structure's natural frequency spectrum match the frequency content of the local earthquake. If the earthquake is large enough and such resonances are present, then seismic damage to the structure may be extensive, e.g., spall, cracks in major structural components, complete failure, etc. But in this case, visual inspection techniques should alert evaluators to the presence and form of earthquake-induced damages, so that structural vulnerabilities induced by local seismicity should be readily and accurately assessed immediately following a large earthquake.

  The more difficult inspection situation occurs when structures are subjected to many low-intensity earthquakes, so that visual inspections might not be sufficient to determine the compromised state of the structure. In this case, more intensive inspection techniques would be required, e.g., non-destructive evaluation using image analysis techniques or acoustic methods, or destructive evaluation of representative concrete samples. Small-intensity vibrations would be expected to produce micro-scale damage (e.g., invisible tensile cracks, concrete fatigue, etc.), and the cumulative effect of such damage to the concrete structural components may substantially compromise structural integrity in a manner similar to other environmental hazards such as aging or corrosion. So magazines in regions where low-intensity earthquakes are common deserve more careful consideration of their structural health.

Another related dynamic load that affects these structures is the shock loadings that magazines are subjected to during site munitions demolition activities. These blast loadings propagate through the ground in a manner similar to seismic events, but there are substantial differences between these two types of loading. So the question of whether nearby blast loadings can create structural vulnerabilities similar to those created by low-intensity seismic events is relevant.

The key consideration is whether the blast loadings can excite resonances in the magazine structure, and it appears that local blast loads can indeed provide similar effects to earthquakes. Blast loads are impulsive in their frequency-domain behavior, so that they possess a broadband nature, i.e., they are composed of a wide range of frequencies that include both short- and long-period components. Blast load amplitudes should be similar to those of non-local earthquake loadings, and their broadband nature implies that all modes of vibration for a magazine structure should be excited by at least part of the blast spectrum, so that the overall effect on structural health is likely to be structurally equivalent to that of an earthquake with similar local intensity and appropriately-matched resonances.

Inspected Sites and Associated Selection Criteria

The six sites visited are in locations that have the potential environment to be subjected to several of the items identified that could cause degradation of the structure.

- **Letterkenny Army Depot in Franklin, PA.** Letterkenny is located in a severe freeze/thaw location. It is noted in previous US Army Corps of Engineers Engineering Research and Development Center bridge inspections at this depot that there are serious deterioration effects taking place on the majority of the bridges. The average maximum temperature is 62°F, while the average minimum temperature is 41°F. The average rainfall in this location is roughly 40.8 inches per year. There are also possibilities that other environmental effects can be taking place on these structures such as carbonation, alkali aggregate reactions, de-icing salt reactions, structural movement, and shrinkage issues.

- **Sierra Army Depot in Herlong, CA.** This location provides an excellent venue for examining the effects of seismicity on explosives storage facilities. Its location just east of the northern terminus of the Sierra Nevada mountain range provides a good historical record of low-level seismic events within the Honey Lake fault complex. Given the depot's long history of ammunition demilitarization activities (which began in 1947 and continued until 2001), the Sierra depot provides a good opportunity for inspections targeted towards identifying structural deterioration caused by both high-strain-rate loadings such as blasts and earthquakes. The other types of deterioration noticed in this area may include freeze/thaw, alkali aggregate reaction, de-icing salt reactions, and carbonation.

- **Red River Army Depot in Bowie, TX.** The site is located just below the freeze/thaw line across the central United States. The average low temperature for Bowie, TX is 54°F. Other types of deterioration effects that may become an issue are carbonation, and alkali aggregate reaction.

- **McAlester Army Depot in McAlester, OK.** This location will provide unique data collection opportunities because it was initially a Navy base and the structures are of a Navy design. This location is basically on the major freeze/thaw line across the US. The average low temperature in McAlester is 28°F. Other types of deterioration that may be seen at this location could be alkali aggregate reaction, and carbonation. The ammunition demilitarization activities a McAlester should also help provide a baseline for comparison with seismic sites such as Sierra, so that the effects of seismicity and nearby shock loadings can be better studied.

- **Milan Army Ammunition Plant in Milan, TN.** This location was chosen based on a previous unintentional explosive event that occurred in an ECM. Sampling at this location would include forensic sampling of the damaged ECM as well as similar intact structures. Milan is located above the major freeze/thaw line in the US. The average maximum temperature is 69.5°F, with the average minimum temperatures being 56.7°F. The average rainfall per year is 54.4 inches. Other major causes of deterioration could be carbonation, shrinkage, structural movement, de-icing salt reactions, and alkali aggregate reactions.

- **Wheeler Army Air Field on Oahu Island, HI.** This location was chosen based on the tropical environment and seismic events that have taken place on the Hawaiian Islands. These islands are also noted to have very acidic soils. The ECMs on this site are unique as they are built into the side of the mountain plateau. This will be a great site to investigate causes of deterioration of reinforced concrete ECM structures. Other likely deterioration effects that could be in play are alkali aggregate reactions, structural movement, shrinkage, and carbonation.

Inspection Processes

Inspection processes details were better understood and adjusted as the site visits took place. The logistics of getting to and on the installations may be of more magnitude that expected. There are many factors that have bearing on what sites and what time the site visit can take place. The inspection team must carefully coordinate with site personnel to schedule a visit that does not adversely affect installation missions. Fortunately, but most likely not representative of future efforts, the site inspections under this effort were mostly performed on empty ECMs. Visual inspections were performed for each ECM at all the sites visited. Non-destructive and destructive testing was performed at the Milan, Letterkenny and Sierra sites and the core samples were analyzed in the laboratory. The site inspection teams included members from USAESCH, ERDC and the OU/CEES.

Below are the general steps taken for sites visited during this effort:

- Site selection
- Contact and coordinate site visit with installation
- Information gathering related to the ECMs prior to visit
- Evaluate need for testing equipment and make necessary arrangements
- Visit site, in-brief installation personnel, and perform inspections
- Consolidate inspection notes and data
- Out-brief installation personnel

- Perform lab testing of samples
- Input information from visual inspection and lab results into data base
- Recommend remediation as needed to address degradation
- Perform structural analyses to better understand ECM structural performance and observed degradation.

Types of Inspection

The data needed to evaluate degradation effects were captured on a previously developed inspection checklist. There were four types of inspections utilized in this effort to gather the data to determine effects of degradation on the ECMs:

- Visual inspection,
- Non-destructive testing,
- Destructive testing, and
- Laboratory analyses

Visual inspections of the ECM building elements (walls, pilaster, doors, earth cover, etc.) were performed to observe obvious signs (cracks, moisture or water, discoloration of concrete, etc.) of degradation or potential for degradation.

Non-destructive (ground penetrating radar (GPR)) testing was utilized to locate steel reinforcement and to determine concrete cover.

Figure 4 Non-Destructive Testing

Destructive testing was performed to gather sample for laboratory analyses. See below for example of core drilling. Repairs were made for all areas where sample was intrusive.

Figure 5 Destructive Testing

Inspection Checklist

There were two lists developed to contain the information related to the ECM needed for input to the data base. One list is a very comprehensive list that was used as the basis for the data base content. The other list is a shortened version that was edited to contain the items that could be obtained mainly from the site investigation. The development of a 'user manual', with examples, for the site investigation lists is planned. Excerpts from the list used for the site investigation are shown below in Figure 6.

<u>GENERAL INFORMATION</u>

Location (Base Name): ____

ECM Number (Building Number) ____________

Steel Tag Number on Door ____________ **Replaced With Tag Number** __________

Site Label Number____________________(located inside magazine on interior headwall)

Location Comments: ____

____

Overall Condition Rating: _____________

Type of Construction: RC Boxed Steel Arch RC Arch

Date of Construction: ____________ or Unknown

Series No. / Dwg No. : __________________

Interior Magazine Dimensions: _________ high x ________ long x _________ wide

Length taken from: interior of headwall **or** door jamb **or** exterior of pilaster

<u>HEADWALL</u>

Pilasters Adjacent to Door:

Dimensions: _______ H x _______ W x ______ T

Left Pilaster Condition:

Cracking:	None	Minor	Moderate	Significant	Major
Spalling:	None	Minor	Moderate	Significant	Major
Delamination:	None	Minor	Moderate	Significant	Major

Right Pilaster Condition:

Cracking:	None	Minor	Moderate	Significant	Major
Spalling:	None	Minor	Moderate	Significant	Major
Delamination:	None	Minor	Moderate	Significant	Major

Pilaster Comments: ____

____

Head Beam:

Dimensions: _______ H x _______ W x _______ T

Concrete Condition:

Cracking:	None	Minor	Moderate	Significant	Major
Spalling:	None	Minor	Moderate	Significant	Major
Delamination:	None	Minor	Moderate	Significant	Major

Head Beam Comments: ____

____

Figure 6 Site Inspection Checklists

Visual Inspection Results

A total of one hundred twelve (112) magazines were visually inspected. Physical samples (core drilled) were taken from three (3) of the sites and tested in the laboratory at ERDC-WES (Vicksburg, MS). Lab results will be discussed in more detail in ECM paper 2.

Below are a few visual inspections items noted:

Cracking:

- At the top of the arch, there generally were 1 to 3 longitudinal cracks running the length of the igloo. These cracks were located at: the center of the arch, 4-6 feet left of center, and 4-6 feet right of center.
- The floor slab generally had the same longitudinal cracks as the arch. There were generally 1 to 3 longitudinal cracks running along the length of the igloo. These cracks were located at: the center, at 4-6 feet left of center, and 4-6 feet right of center.
- There was often one large transverse structural crack (1/4” to 1/2” wide) located near mid length of the ECM. In addition to the large transverse crack, there were also smaller transverse cracks along the length of the building.
- The back wall often contained a small vertical crack at the center of the wall from the top of the footing wall to the vent box.
- The head wall generally contained 2-3 cracks radiating from the corners of the doors and some showed impact damage at the door jambs where heavy machinery had likely bumped the door jamb.
- Igloos with heavier head walls, or headwalls with pilasters, often contained cracks at 45^0 radiating out from the headwall longitudinally.

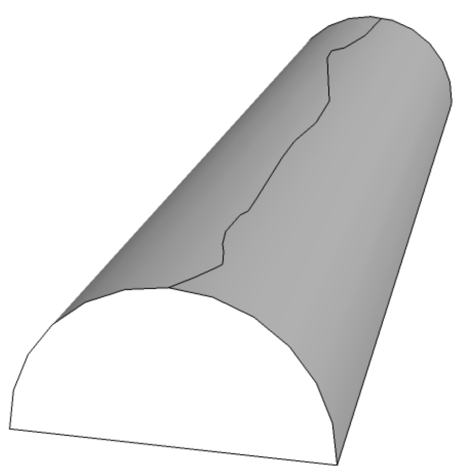


Figure 7 Longitudinal cracks along the apex of the arch

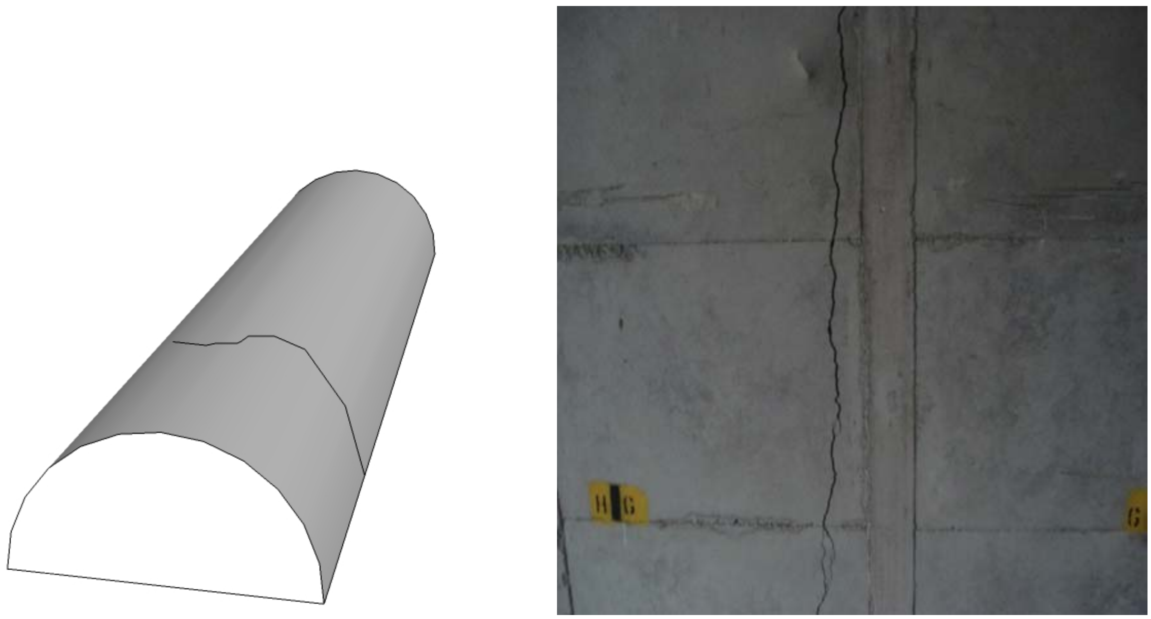


Figure 8 Transverse cracks (generally near mid-length)

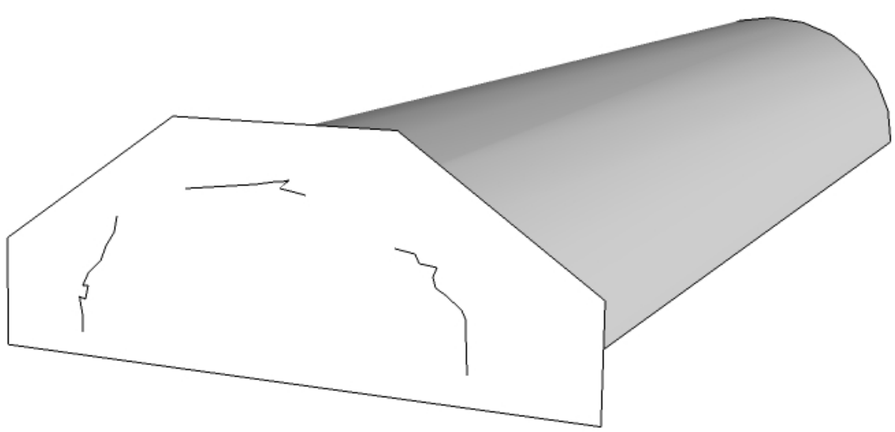


Figure 9 Cracking at the headwall along the arch

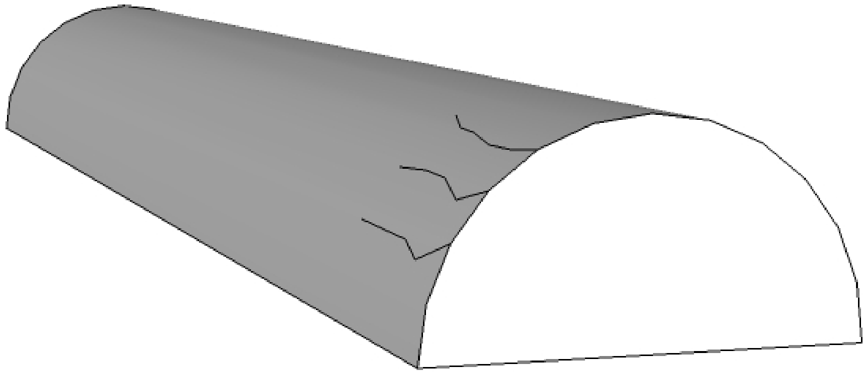


Figure 10 Cracks radiating from the headwall

Spalling: Loss of concrete cover promotes corrosion and loss of steel reinforcement cross sectional area, which adversely affects concrete strength.

Figure 11 Spalling (insufficient concrete cover)

Database Development

Most engineering problems, and specifically civil engineering problems, are well defined and the pathway for determining solutions is well traveled. In these cases, the design requirements are understood from the beginning. This is not the case for the requirements and structure for the ECM database. The database parameters are not well defined and must be iterated over the course of successive design, implementation, and feed-back steps. Throughout the design process the requirements are discovered and the design is altered to accommodate the changing requirements in a spiral process. This spiral design process is common in software development and information systems. The result is a high quality engineering product developed cost-effectively even when requirements are fuzzy and the work to be done is unprecedented.

Design Process

In this project, three successive iterations were used to develop a useful final prototype design, and this prototype can readily be reused to develop a production-grade, scalable, secure, and usable data archive for use in long-term monitoring of earth-covered magazines and similar military infrastructure. The basic outline of these iterations is shown in the figure below, where three iterations of design, implementation, delivery, and evaluation are shown.

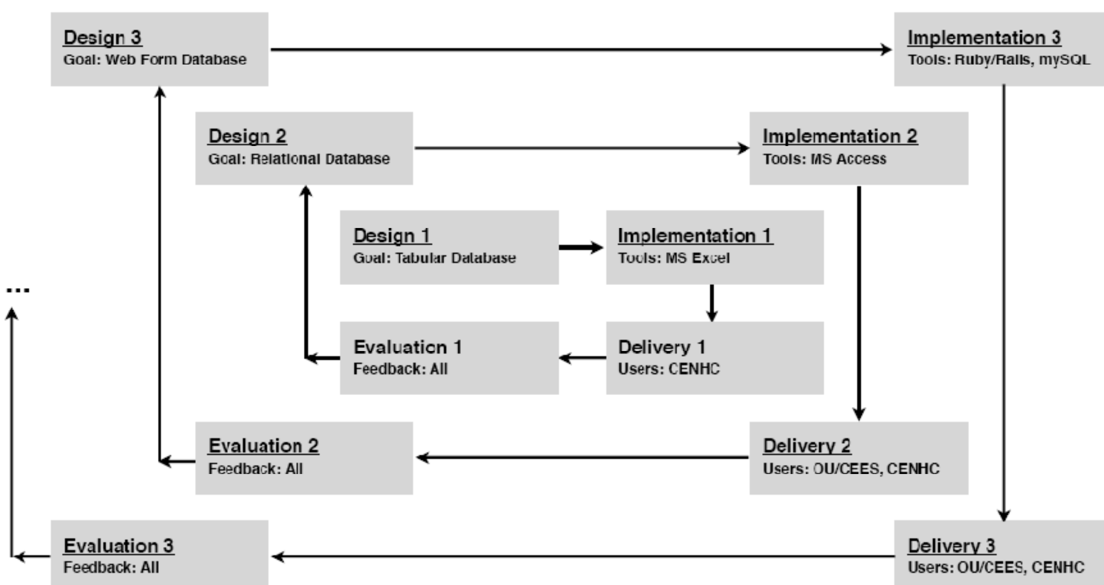


Figure 12 Spiral Design Path

Database Prototypes

One of the most important principles of iterative design is to start somewhere and do something, so that some kind of product can be shown to users to permit better characterization of initially uncertain requirements. On the first iteration, this product does not necessarily need to be functional or complete: in fact, mere by-products of the design process (e.g., presentation materials outlining the basic elements of the user interface, use-case scenarios, wish lists for features, etc.) are often sufficient to prime the pump of successful iterative software development.

In this project, that initial working model (V1) was provided by a spreadsheet-based implementation of a prototype data archive developed at CEHNC. This spreadsheet used Microsoft Excel to implement a tabular representation of the inspection documents, and thus provided a useful starting point for discovery of requirements for this project. The primary limitation of a spreadsheet-based database is that its format is tabular, so deviations from a table-oriented format are not easily handled (and the subsequent inspection processes demonstrated that this case arises in practice). In addition to this limitation, spreadsheets are readily corrupted during use (leading to errors in the database), and they do not provide support for auditing data, i.e., recording the circumstances under which data fields were added or changed. In spite of these limitations, the spreadsheet prototype V1 of the data archive provided considerable function, and permitted the project team to better identify requirements.

The second (V2) prototype developed for this project was designed to remedy some of the limitations of the spreadsheet-based approach. The team decided to utilize a relational database (RDB) instead of a spreadsheet as the underlying computational technology, because an RDB permits a more flexible layout of data, including variants and more complex data schemas. This initial RDB implementation was realized using Microsoft Access 2003 and 2007. The MS Access version of the database demonstrated that the greater flexibility of a relational database was a good fit for the emerging needs of this project, but problems with this approach were quickly identified. For example, although the current version of Access is the Office-2007 variety, U.S. Army facilities are still using the 2003 version due to various cyber security problems encountered in supporting newer versions of MS Office products. The 2003 version of Access is relatively limited in terms of data types supported, e.g., it is difficult to extend and retrieving images in the data archive. In addition, all versions of MS Access are serial, i.e., they utilize only one processor at a time, and hence do not scale well to multiple users. This constituted a serious limitation for a production-grade database, as scalability was discovered to be an important requirement for the data archive. The most important requirement discovered was the need for a web interface, so that remote access to the database could be implemented, including appropriate security measures to ensure the integrity and secrecy of the data archive. Grafting a web-browser interface onto MS Access is a difficult (if not impossible) job, and hence the final requirements of scalability and web-accessibility were identified early in the project lifespan so that a third iteration of the prototype database could be developed.

The third and final prototype iteration (V3) was designed using the following requirements:
• the data archive needed to be scalable to handle multiple users and large databases, so that concurrency in both the number of users and the number of CPUs was required,
• the data archive should be accessible remotely, initially through a simple web browser interface, and perhaps ultimately with this web interface supporting mobile devices that can be carried into the field to gather data directly during inspections,
• the data archive must be relatively easy to develop, but also permit future refinements without having to abandon supporting technologies and existing code resources,

• the database underlying the archive should be industry-standard, with well-defined and well maintained application programming interfaces (APIs), so that the prototype could be refined over time without undue risk of becoming unsupportable as computational technology improves in the future,
• the archive must support all relevant functions either in its initial implementation, or upon future programming improvements, including data entry and retrieval, editing data, deleting records, adding content, and insuring that appropriate audit trails are established and preserved to guarantee the accuracy of all provenance information,
• the archive should be reasonably secure, with security features present in its initial version, and with improved security available over time with additional programming effort,
• the archive should support multiple users, and provide for the potential for access control, e.g., different users having different rights and responsibilities in using the archive,
• the data archive and all supporting software should be cost-effectively developed within a short timeframe and a limited budget as appropriate for this exploratory project.

These requirements naturally led to a web-based application using the industry standard MVC software architecture. MVC is an abbreviation for Model/View/Controller, and this architecture is widely used in interactive computing settings.

MVC applications can be made secure, because access to sensitive data in the database is mediated by various software components in the controller layer, which can be designed and implemented so as to enhance security, e.g., by requiring user identification and authentication via a logon process, as shown in the following figure:

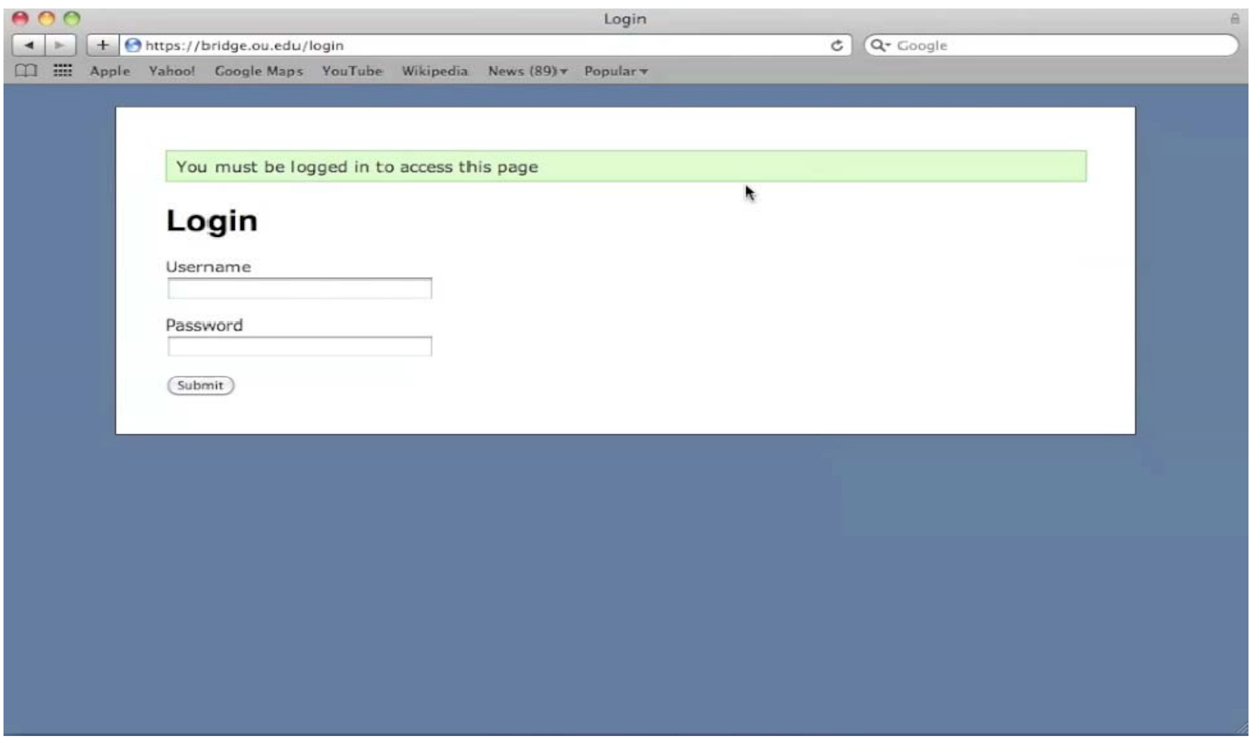


Figure 13 Database Login Page

In order to implement this third iteration of the prototype database, the project team selected the Ruby-on-Rails programming environment, because this combination of a flexible programming language (Ruby) implemented using a web-service framework (Rails) has proven to be a useful and cost-effective means for rapid design and deployment of web-based applications that involve heavy use of a back-end database. This open-source programming environment has been used to develop such web-based environments as Twitter, YellowPages.com, and Hulu.com, and it has proven to be a good choice for design and deployment of the ECM data archive.

The database components that support the Ruby/Rails software are provided by MySQL, which is an open-source industrial-strength implementation of a SQL (Structured Query Language) relational database manager. MySQL provides high-performance database capabilities when implemented on low-cost computers, e.g., PCs and Macs, and can support many users accessing large datasets without substantial degradation in performance. In addition, it is relatively straightforward to replace the MySQL database components if additional performance is required, because the SQL accesses are mediated via the model and controller components of the MVC software architecture. But the simplest way to improve the performance of a MySQL database is to use a faster underlying computer, and with multiprocessor/multicore computers based on Intel architectures so readily available, the use of the Ruby/Rails/MySQL software stack should prove sufficient for all foreseeable future requirements of the ECM data archive.

Data Input

The next figure shows the creation of a new collection of ECMs, in this case for the Letterkenny Army Depot. The links at the upper-right of the web browser display provide the user with easy access to the key functions of the archive, including the ability to add users, examine audit trails for data, and customize profiles that determine how the system is configured.

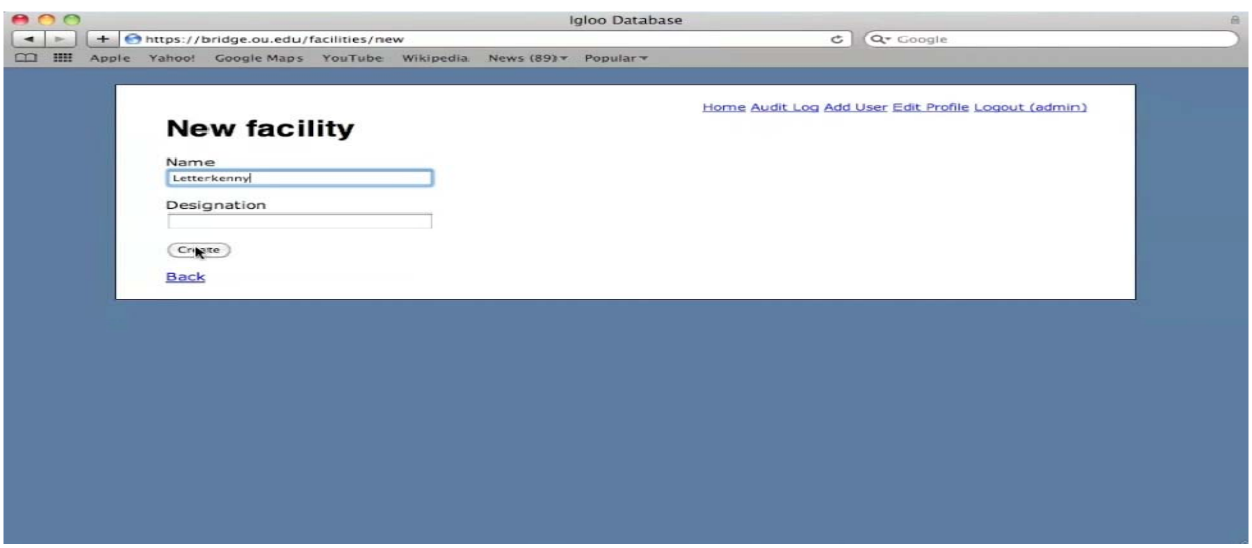


Figure 14 Creating a New Facility in the Database

Once a facility has been created, the specific ECM information that has been gathered via inspection processes can be input to populate the data entries for this facility. The various inspection fields as shown in the figure are implemented as fields in the database, and a web-based graphical user interface is implemented so that the field inspection data is naturally mapped to fields drawn on the web browser's window. The basic idea is diagrammed in the figure below, where a written inspection record is overlaid on the associated web form.

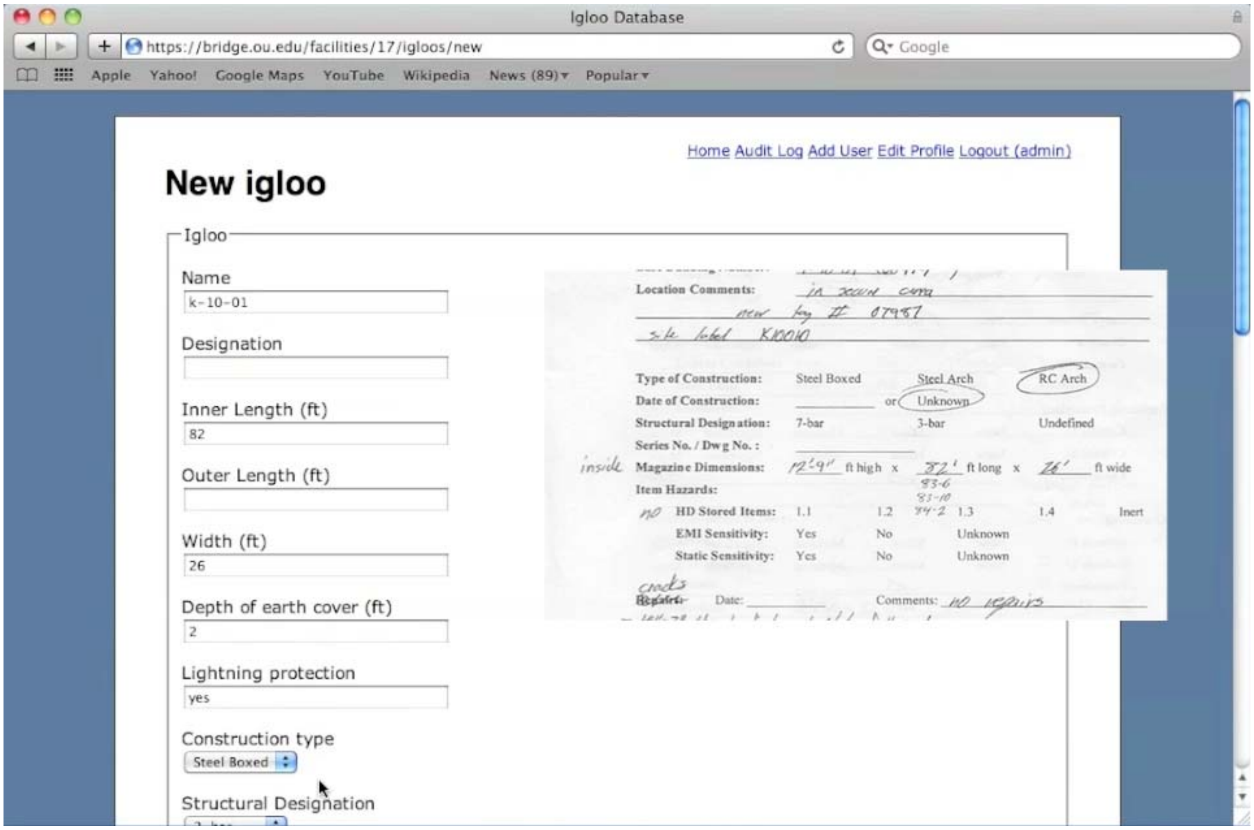


Figure 15 Data Input

Using these web forms, the current inspection records can easily be input into the database, and this effort can be carried out virtually anywhere web access is available. One desirable long-term goal for the data archive is the use of portable web devices, e.g., an iPhone. These digital assistants could be utilized to eliminate much or all of the writing and paper used to input data into the ECM archive with relatively little programming effort.

Audit Features

Any archive containing sensitive data must not only be secured, but it also must implement auditing features to track input, revision, and deletion of data. The provenance of all data in a sensitive archive must be tracked so that data events (e.g., creation, revision, deletion) can be identified and logged for auditing purposes, to ensure that all data is properly curated and appropriately trusted. The current prototype permits this auditing function. The following figure shows how auditing information is presented to the user for that given site. The formatting is quite spartan in this prototype, but improved formatting is easy to implement once appropriate requirements have been discovered and recorded.

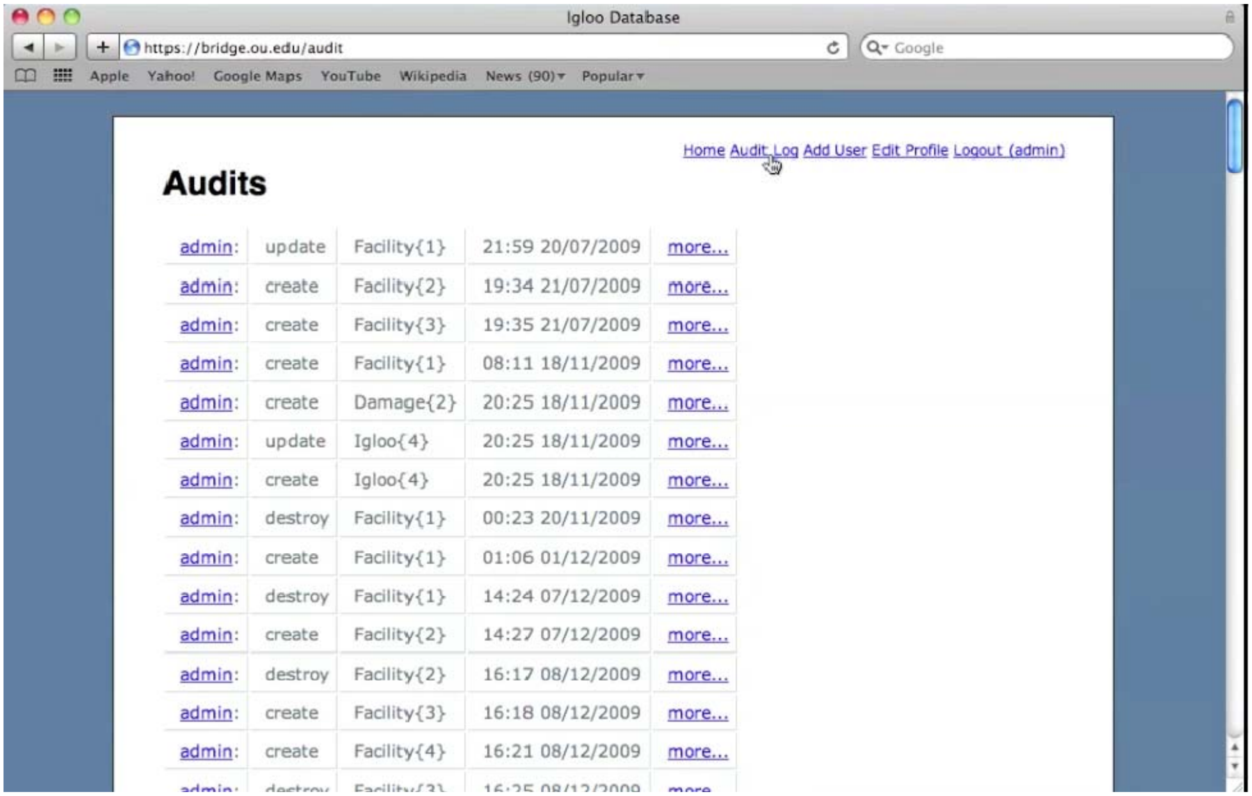


Figure 16 Audit Record

Reports

Report generation using the ECM data is similarly bare-bones, and this function is also extensible once the particular requirements for reports have been identified. In the current version of the data archive, simple on-screen reports are selected by first selecting a particular ECM from the list provided for a given facility. Then the data for the selected ECM (or "igloo") is presented in a simple tabular representation. Additional formats are currently being explored by the project team, including more comprehensive reports that tabulate relevant data over an entire facility.

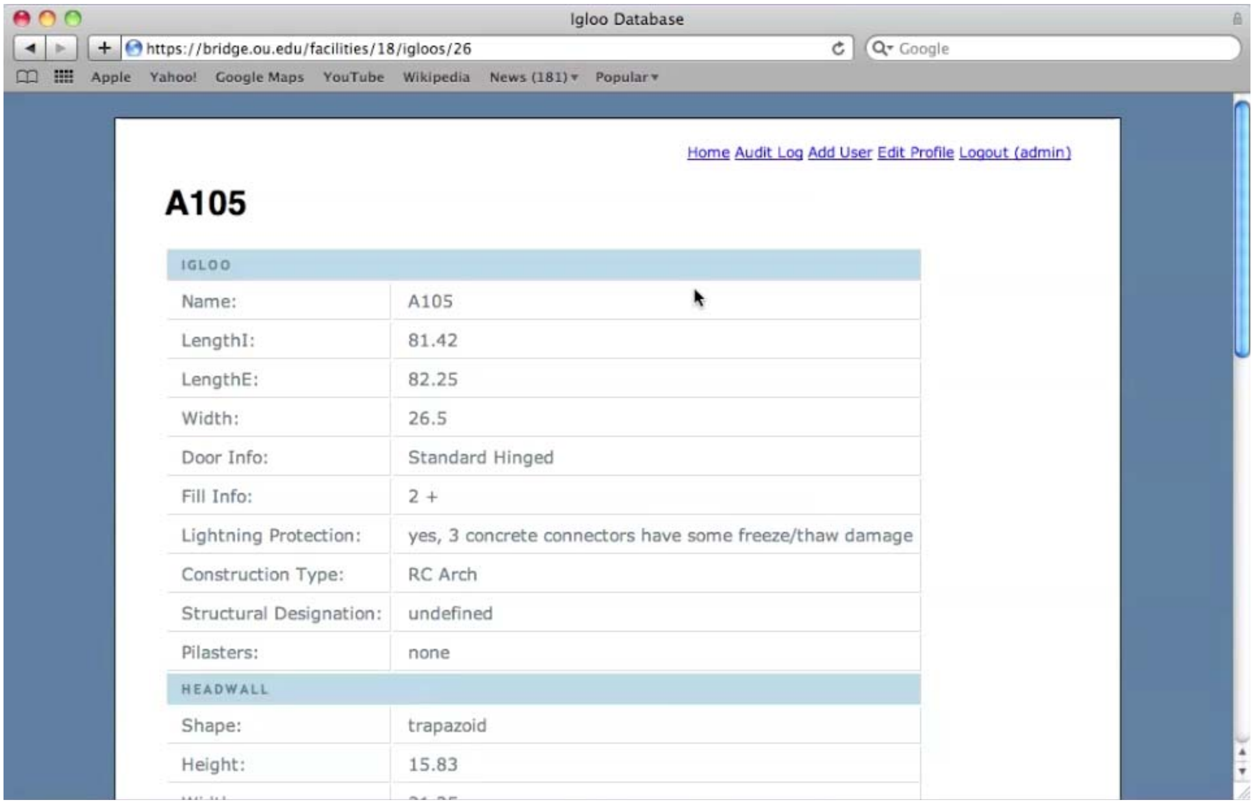


Figure 17 Database Report

Versioning of the data is provided so that configuration management can be carried out on all the data present in the archive. This not only provides a means for auditing, but also permits errors to be rolled back out of the system because earlier versions of the data are stored separately. This provides an additional layer of safety for preserving the integrity of the data.

Ownership of Database

The prototype web-accessible data archive utilizes client-server architecture, with the database running on a remote server platform, and users accessing the data archive through web-browser clients. This provides a cost-effective, easy-to-use, and scalable implementation of the ECM data archive, but it also creates the natural question of where the server should be located, i.e., who should own the data archive. In its current prototype implementation, the server is located on a high-speed network within the University of Oklahoma network infrastructure, but a better long-term approach for ownership would be to place the archive within the DoD network structure, so that as data is added, appropriate levels of long-term maintenance and operational resources can be provided for both hardware and for software support. In the long term, the project team suggested that the data archive servers should reside at DAC, and the web-based client architecture can be made available to all relevant DoD and associated stakeholders. The process of porting the data archive to a new location is the subject of an auxiliary project document that is currently under development, in the form of an installation and user guide for long-term stewardship of the ECM data archive.

Conclusions

For this prototype effort, site inspections, laboratory testing and structural analyses indicate varying levels of concrete degradation in concrete magazines. The results of the inspection/analyses need to be evaluated more closely to determine if there are patterns of degradation that can be used to chart a more informed path ahead for future work.

43% are estimated to have "Good" structural health, 50% are estimated to have "Fair" structural health, and 7% of the magazines are estimated to have "Poor" structural health.

"Cracked" concrete was observed during site inspections.
Possible causes are:

- site conditions (expansive soils, freeze-thaw, etc.),
- soil not compacted adequately,
- unanticipated construction loads,
- unanticipated point loads (mowing equipment, etc)),
- water infiltration causing spalling,
- results of 'heaving' from freeze-thaw conditions and/or
- difference in stiffness of headwall components vs. arch and sidewalls

Spalling and corrosion of reinforcing steel (rebar) were observed during site inspections.

Recommendations

The results of this initial effort establish there are ECMs in the DoD inventory that have varying stages of 'structural health'. Since magazines with "Poor" structural health were identified, the actual concrete 'break-up' for a degraded structure should be investigated so comparisons to legacy assumptions for structural failure can be performed.

Debris distances for the 'deteriorated' state should be examined in light of current required quantity distances associated with accepted DoD exposures. Efforts to further inspect and store gathered data should be pursued in parallel with the debris study efforts. Further development of the data base should be pursued. Thus far, the inspection procedure and proposed "structural health ratings" have been based on the established nationally used Bridge Inspection Program; further adaptation to storage magazines is needed.

From lab data gathered in this initial effort, an accurate usable methodology to estimate 'remaining service life' based on the visual inspection results should be developed.

Due to limited access to some magazines, it is advisable to pursue analytical methods to predict degradation and remaining service life based on a limited visual inspection.

Initial results show varying levels of 'structural health'. A long term monitoring program is recommended. Periodic inspection results will provide indication of deteriorating health or not and can be used by Master Planners and Safety Personnel in making decisions on utilization of the magazine.

Future inspection efforts should be prioritized considering locations that pose the most hazards to people and assets if an accidental detonation should occur.

References

1. Department of Defense, *DoD Ammunition and Explosives Safety Standards*, DoD 6055.09-STD, February 29, 2008, *Incorporating Change 2, August 21, 2009*.

2. Department of Army Phamphlet 385-64, *Explosives Safety Standards, 15 December 1999*

3. DDESB Technical Paper 15 *Approved Protective Construction (Revision 3),May 2010*

Effects of Aging and Environmental Conditions on Ammunition/Explosives Storage Magazines – Paper 1

Jeff Coulston P.E.

Chief, Structural Branch

US Army Engineering & Support Center, Huntsville (USAESCH)

34th DDESB Seminar, Portland, Oregon

13 July 2010

US Army Corps of Engineers

BUILDING STRONG®

Presentation Outline

- Motivation
- Goals of Study
- Team and Accomplishments
- Concrete Deterioration
- Sites Visited
- Inspections and Results
- Data Base (Web-Based)
- Conclusions/Recommendations

Acknowledgements

- Generous Support of Defense Ammunition Center (DAC) and US Army Technical Center for Explosives Safety (USATCES)
- Various Installations Visited
- Efforts of Team Members

Motivation Driving Effort

- USATCES Concerned About Current Quantity Distances Being Un-Conservative for Allowable Exposures (ex. IBD, PTRD)
  - Milan Accidental Explosion Revitalized Concern
  - For QDs governed by Secondary Debris Distances
  - PES (Donor) is an "Aging/Degraded" Structure
  - Reinforced Concrete Structures Targeted for This Effort
    - Specifically Earth Covered Magazines

Is Concern Warranted?

- How does Aging and/or Degradation of Reinforced Concrete Structures Effect ‘break-up’ and Debris Distance?
  - Weaken Structure Due to Cracking – Stress Concentrations
  - Reduced Area of Reinforcing Steel (Rebar)
  - Construction Quality
    - Bond Between Concrete and Rebar
    - Presences of Voids
- Accident Data Justifies Concern

DoD ECM Inventory

- Over 15,000 Magazines with Critical Munitions and Volatile Compounds
- Some Located Near Populated Areas
- Many Have an Average Age of 50 Years Old
- How “Healthy” (Structural Health) Are They?
  - How Many ECMs Are Not ‘Healthy’?
- DAC Obtained Funding to Initiate Efforts to Find Out

Goals of Study

- Gain Accurate Estimate of Scope of ‘Problem’.
- Collect and Archive Data
- Identify Practical Remediation Methods
- Create Long-Term Health Monitoring Program

Inspection Team

USAESCH

Primary: Project Management
Secondary: Structural Engineering, Inspections

ERDC

Primary: Inspections, Material Science
Secondary: Information Technology

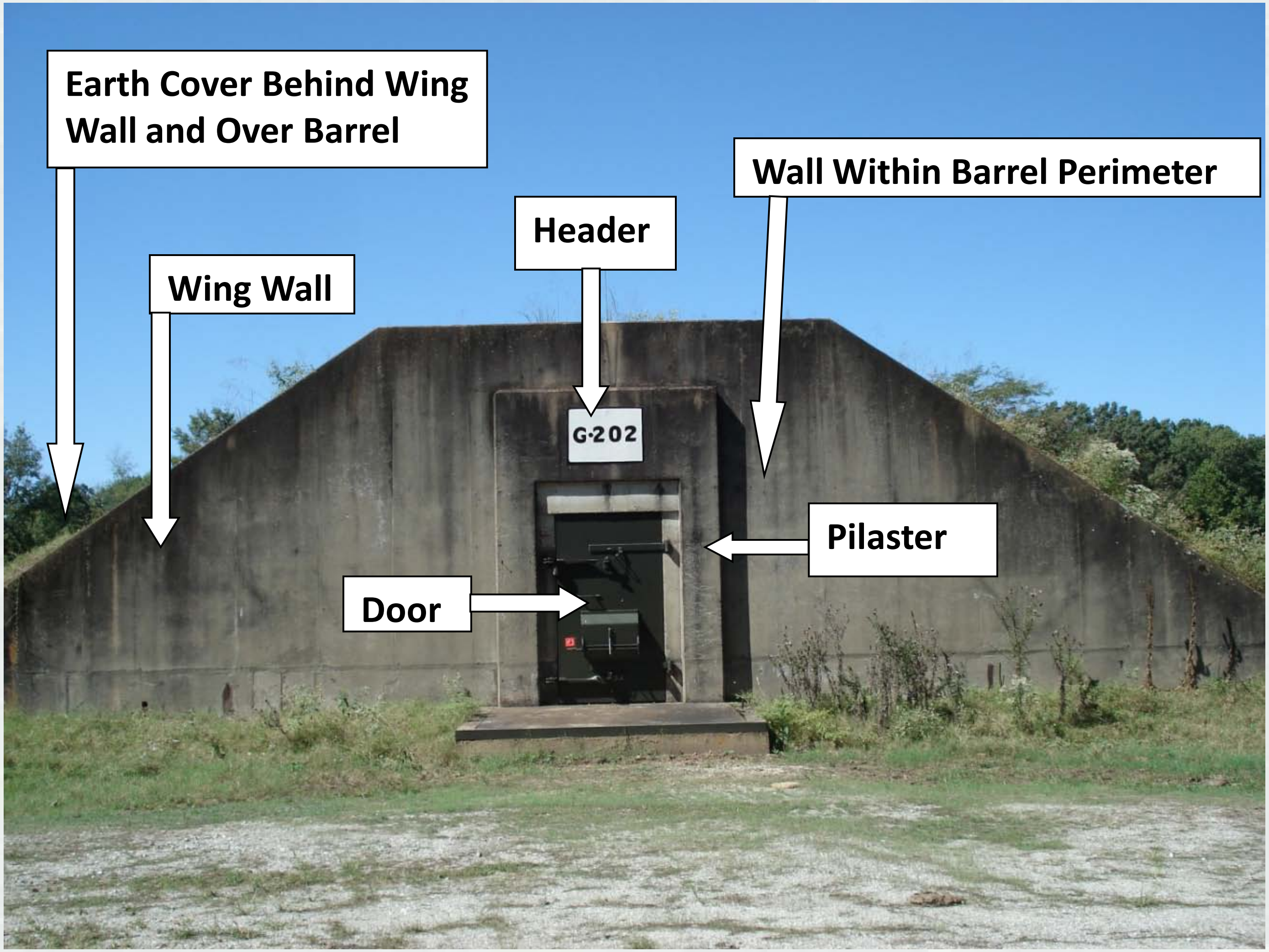
OU/CEES

Primary: Structural Engineering, Information Technology
Secondary: Inspections

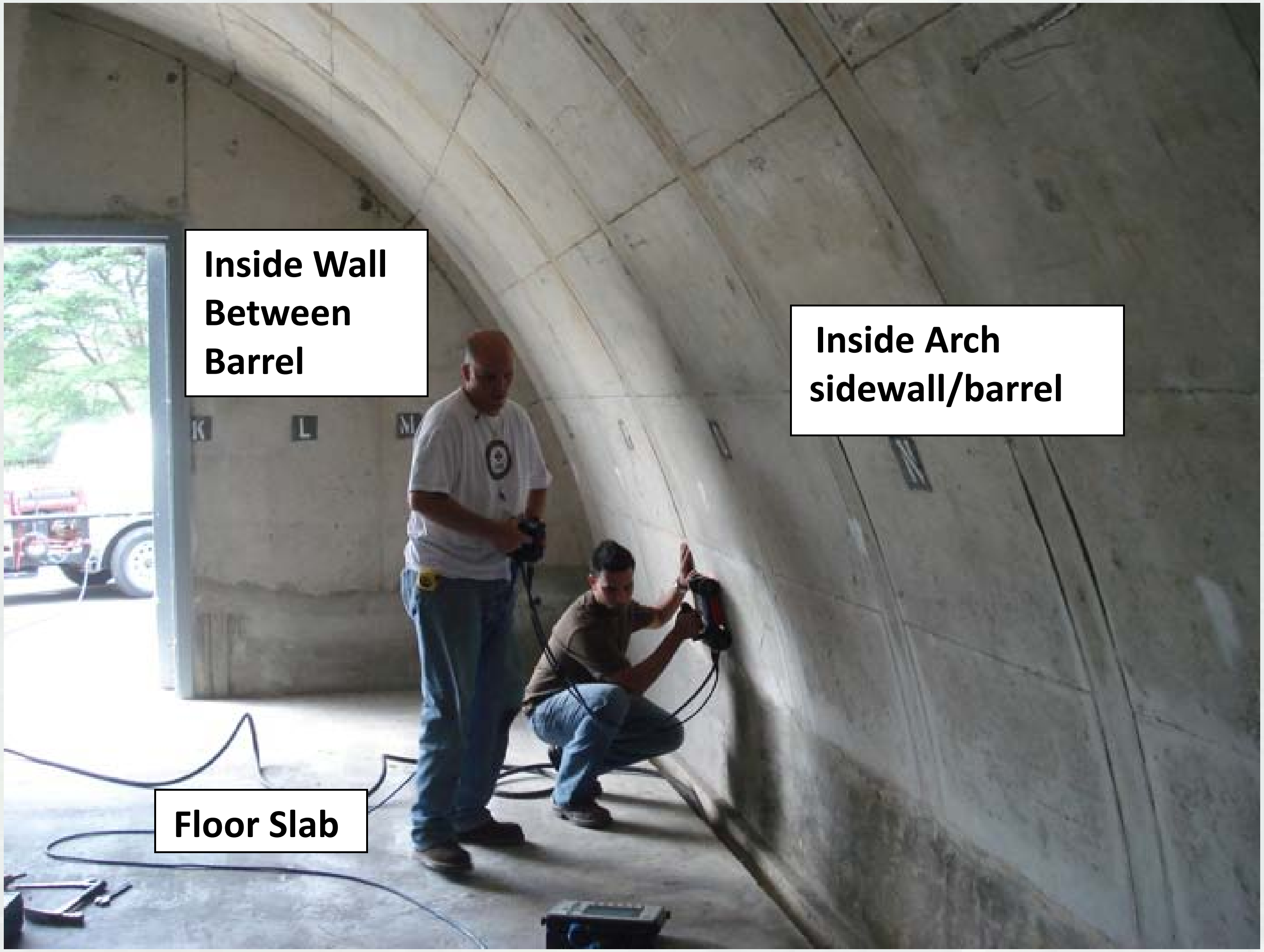
Accomplishments Toward Goals

- Developed a Data Collection Plan
  - Developed Site Inspection Checklists
- Collected Data
  - Leveraged Efforts with National Bridge Inspection Program
  - Visited 6 Sites (CONUS and OCONUS)
  - Developed Database (Web Application)
- Identified Remediation Techniques
- Suggestions for Long Term Monitoring Programs

ECM Components



ECM Components



Concrete Deterioration

- Covered in More Detail in ECM Paper 2
- Chemical Reaction Damage
  - Acid Attack, Aggressive-Water Attack
  - Alkali-Carbonate Rock Reaction (ACR)
  - Alkali-Silica Reaction (ASR)
  - Sulfate Attack, Carbonation, Rebar Corrosion
- Mechanical Damage
  - Freeze/Thaw, Structural Movement, Shrinkage
  - Seismic Vulnerability

Sites Visited

- A Total Of 112 Magazines Inspected
- Letterkenny Army Depot, Franklin, PA
- Sierra Army Depot, Herlong, CA
- Red River Army Depot, Bower, TX
- McAlester Army Depot, McAlester, OK
- Milan Army Ammunition Plant, Milan, TN
- Wheeler Army Air Field, Oahu, HI

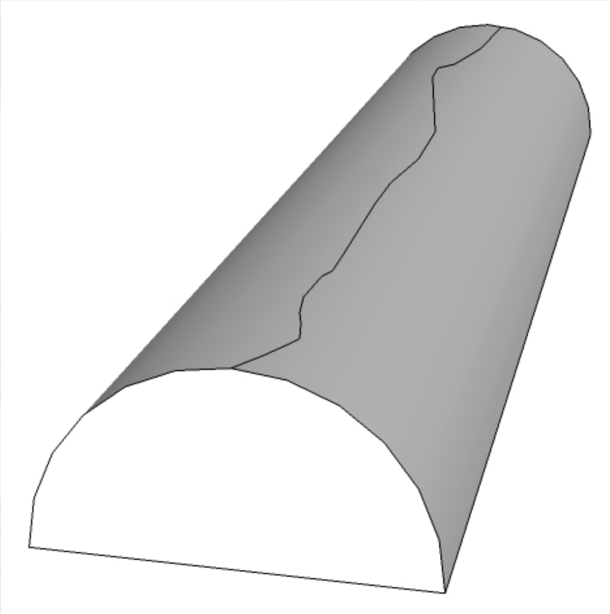
Types of Inspection

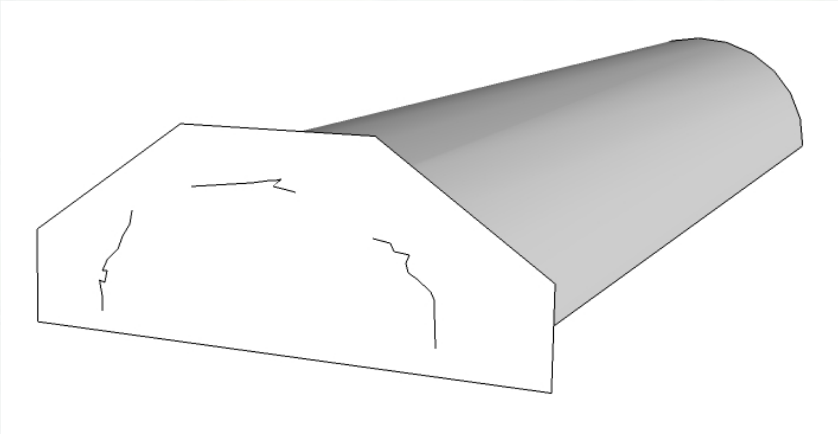
- Visual At All Six Sites
- NDT and DT Done at Three Sites
  - NDT– GPR to Locate Rebar/Check Cover
  - DT – Obtain Core Samples of Concrete and Rebar for Lab Analyses. Concrete Repair Done at DT locations.
- Computational
  - Structural Analyses to Duplicate Visual Findings
- Data Gathered Input Into Web-Based Data Base

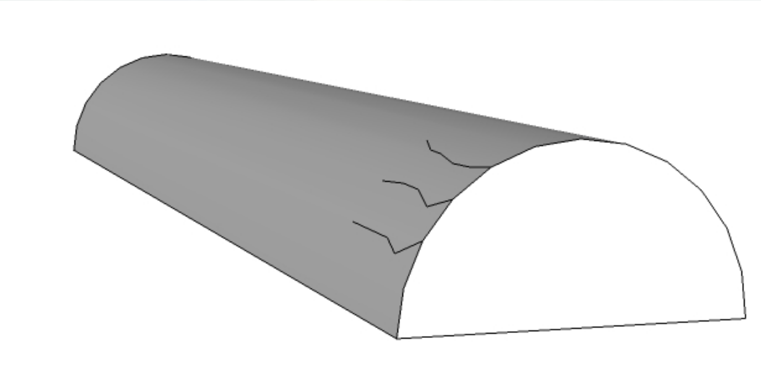
Visual Inspection Results

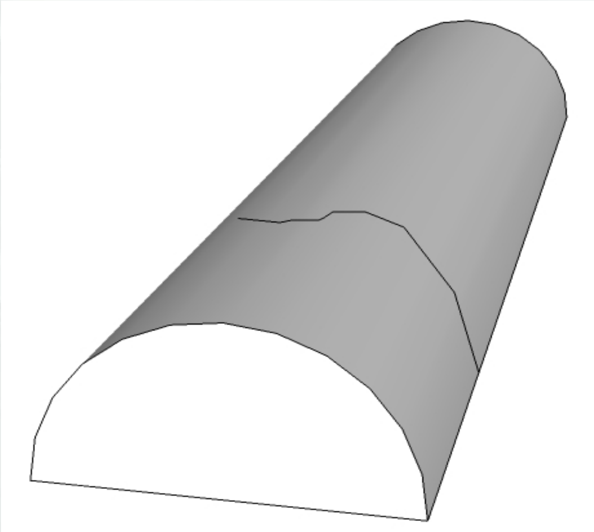
- Cracking
  - Arch (Longitudinal and Transverse)
  - Side and Rear Walls (Longitudinal and Transverse)
  - Headwall
    - Evidence of Impact (“Bumping”) Near Door
    - Along Arch Locations
  - Floor
- Spalling

Cracking









Cracking

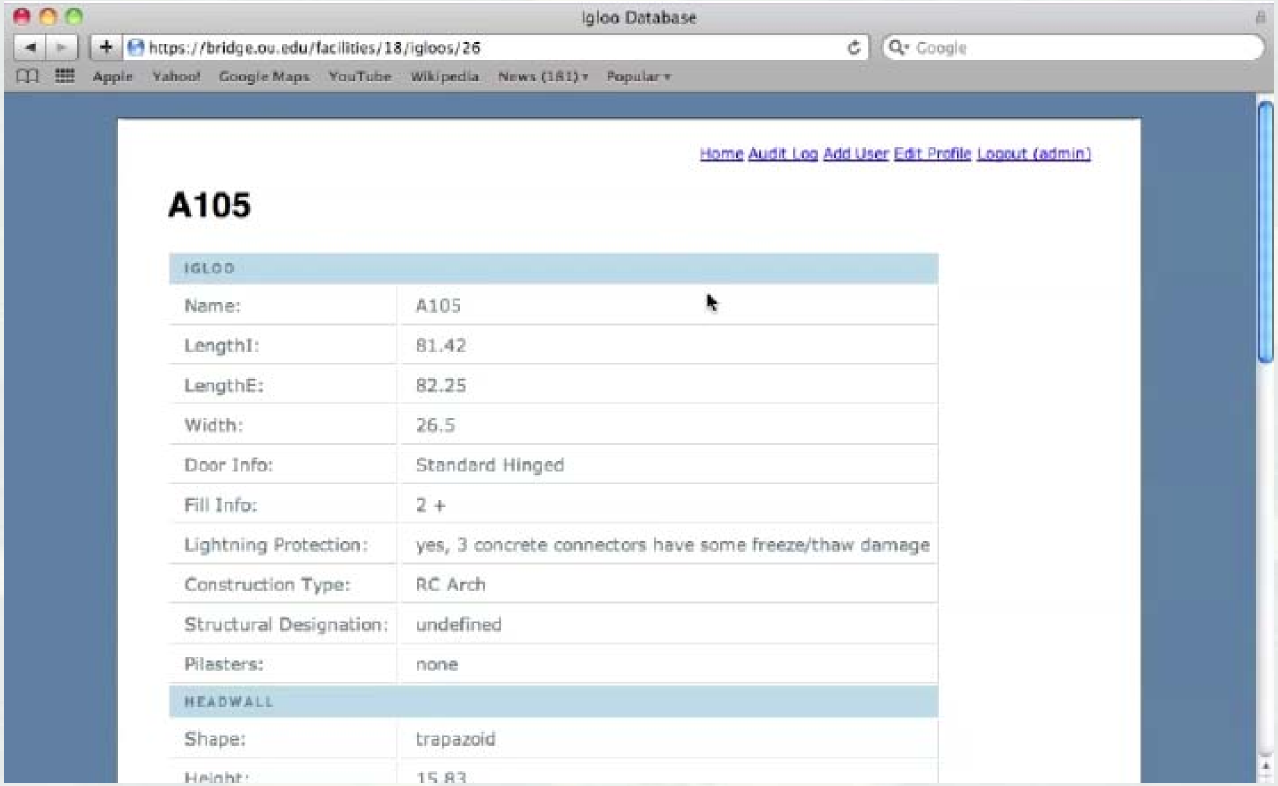
Transverse at Arch Sidewall

Transverse at Arch

Spalling

Database

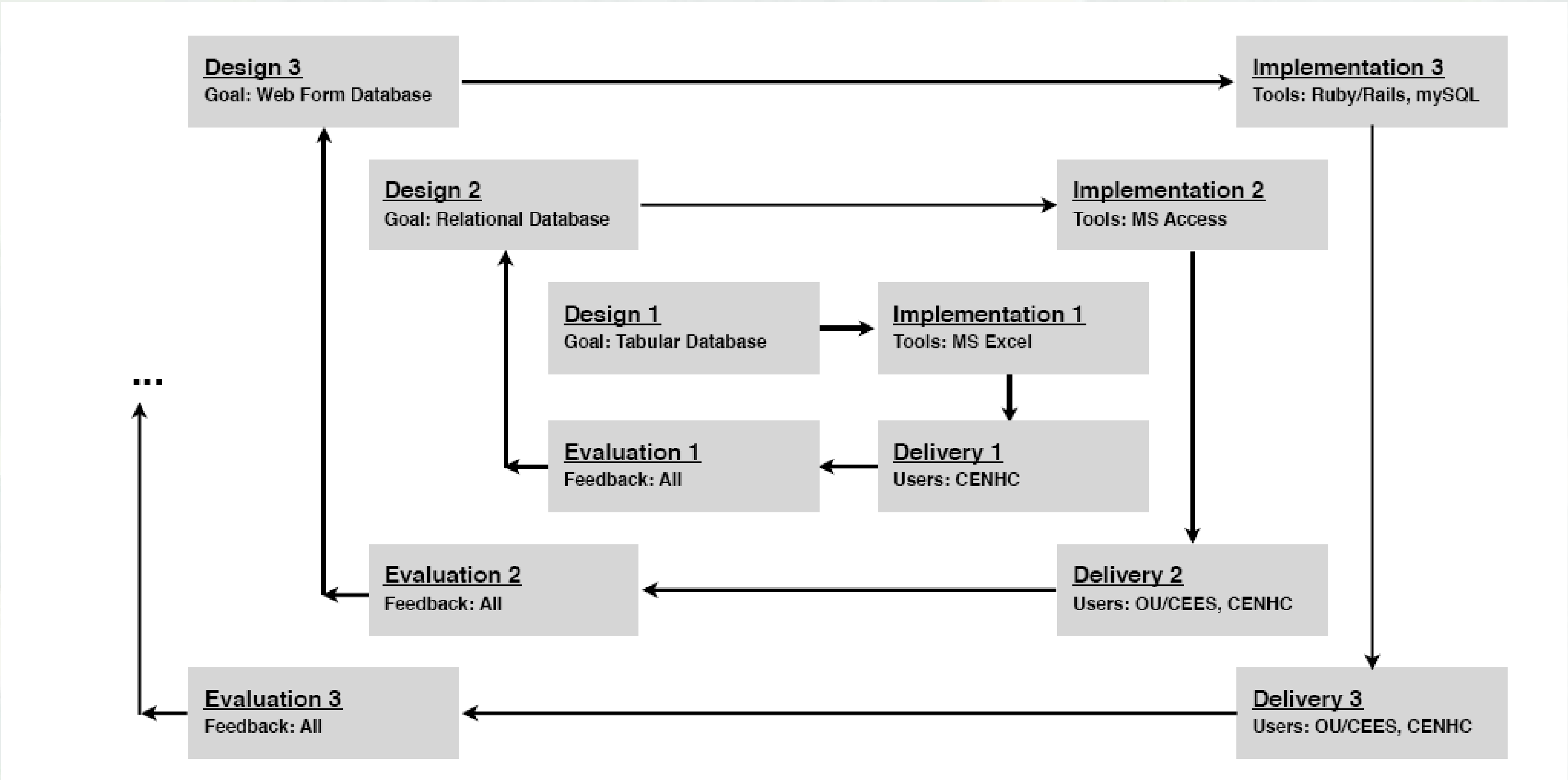
- Purpose
- Design
- Features



Database - Purpose

- Archive data collected on the structural health of aging ECMs
- Structural health ages over decades – software should too
- Database goal - extensibility

Database - Design



Database - Features

- Web accessible – security and ease-of-use
- Captures inspection workflow
- Scalable – handles multiple users and unlimited number of records
- Audit feature – records provenance metadata (data about data)

Conclusions

- Degradation of Concrete Structures Was Observed
- Structural Health Varied
  - 43% “Good”
  - 50% “Fair”
  - 7% “Poor”
- Cracks Were Observed
- Spalling/Corrosion Was Observed

Recommendations

- Address Concern That Current Debris Quantity Distances May Not Be Conservative for Concrete Structures in a Deteriorated State
  - Blast Effects Analyses and/or Testing to Determine Debris Throw from Deteriorated Structures
- Continue Site Inspections to Determine Scope of ‘Problem’
- Continue to Develop Prototype Web-Based Data Base

Recommendations

- Pursue Correlation of Service Life Determination Based on Visual Inspection Results
- Pursue Structural Analyses Methods to Substitute for Detailed Visual Inspection
- In the Short Term: Target Installations That Pose Greatest Risk of Damage/Injury to Assets and People.
  - ▶ Develop List of Installations
    - Consider High Storage Limits of Volatile AE.
    - Consider Exposed Sites and Potential Damage/Injury

QUESTIONS